MASSACHUSETTS INSTITUTE OF TECHNOLOGY

LINCOLN LABORATORY

AN EXTREMELY LIGHT-WEIGHT UHF DIPOLE ARRAY FOR SATELLITE APPLICATIONS

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ABSTRACT

The development of an extremely light-weight, circularly-polarized crossed-dipole UHF antenna array is described. Performance characteristics of the array measured on a full-scale model including gain and VSWR curves are provided. Weighing only four pounds, the array provides a nominal 13 dB gain in the 290-400 MHz band. The unit's light weight and durability makes it very attractive for use in a satellite application.

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I. INTRODUCTION

In anticipation of the possible need for a large array of antenna elements for a UHF nulling system aboard a satellite, Lincoln Laboratory undertook the development of an extremely light-weight crossed-dipole antenna. This development was prompted by a prior investigation which indicated that although large filled apertures provide the best nulling performance, the required payload was prohibitive. Instead, it was found that widely-spaced elements (i.e., a thinned array), distributed about a center element is a reasonable compromise which would provide good nulling and still have a total system weight within reason. One such configuration is shown in Fig. 1. It was established that circular polarization and close to + 13 dB of gain would be necessary for each antenna array element over the 300-400 MHz frequency band. Knowing that an existing space-qualified helix radiator providing this gain weighed approximately 28 pounds, the goals were set to provide an antenna with approximately 13 dB gain but a drastically reduced weight. Since some elements were deployed a large distance from the center element, each outboard antenna pound added two pounds to the total payload because of the required added stiffening of the booms and the larger deployment and holding devices needed to survive the launch environment.

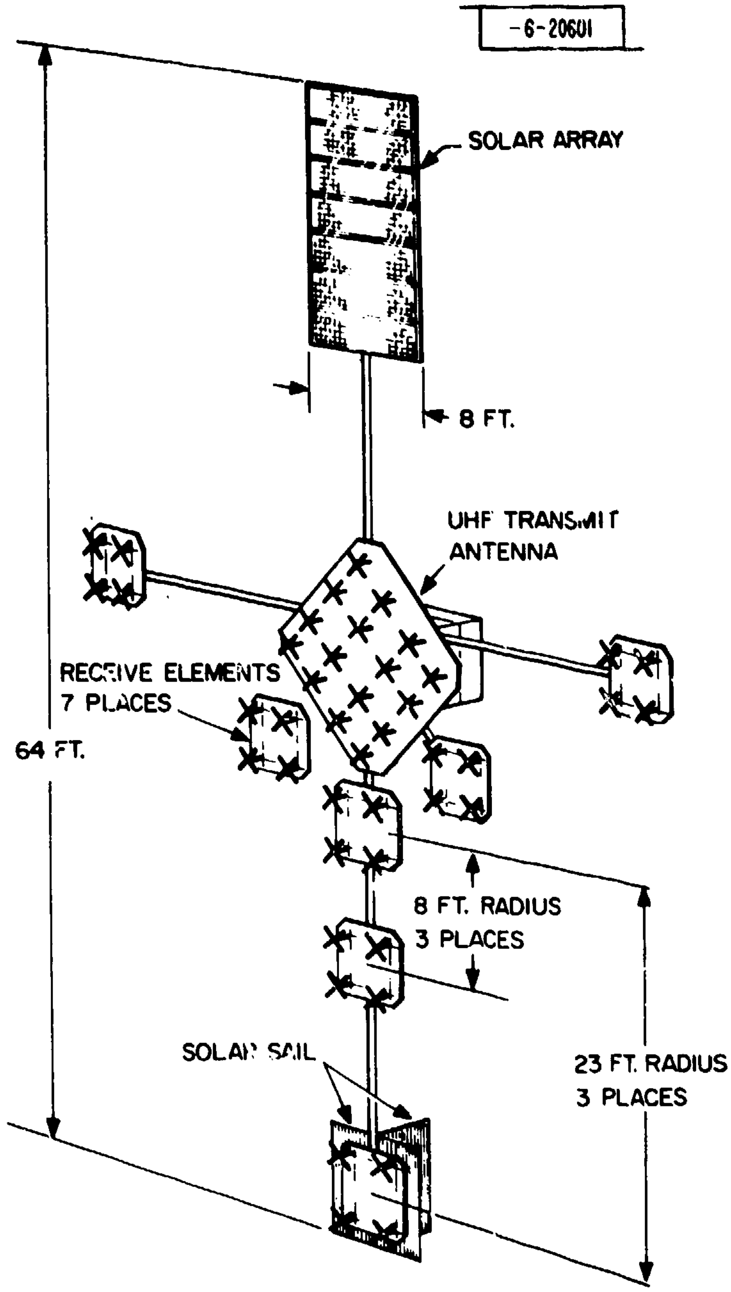


Fig. 1. Lincoln study satellite version No. 2.

II. DESIGN CONSIDERATIONS

Several basic radiating elements were considered including spirals, slots, helices and dipoles. Considering both electrical and mechanical requirements and the space environment to be experienced it was determined the most promising antenna was an array of crossed dipoles over a common ground plane. Calculations indicated that four appropriately spaced dipoles would approximate the gain requirement, and mechanical layouts showed they would provide the most compact configuration, compared to the other candidate antennas. As an example, a 10 turn helix would provide the required gain, but from a packaging standpoint was very unattractive because of its seven foot length.

The gain versus frequency shown in Fig. 2 was calculated for the chosen array configuration and assumes an infinite ground plane. The lower curve is the gain of the elements without impedance matching and takes into account the reflection loss caused by the effect of self and mutual impedance variation, but does not include any feed-network losses. The more nearly constant gain curve in Fig. 2 indicates that which would be realized if the VSWR of the antenna over the entire frequency band were modified to be 2.5 and assumes realistic feed-network losses of 0.6 dB. The basic dipole used in the computer program utilized for these calculations assumed a cylindrical rod of selectable diameter, but tests later confirmed that a thin strip element twice as wide as the rod diameter gives impedance results that are equivalent. As can be seen from Fig. 2, the calculated gain is close to 13 dB over much of the band of interest with a minimum of 12.3 dB at the low end of the band.

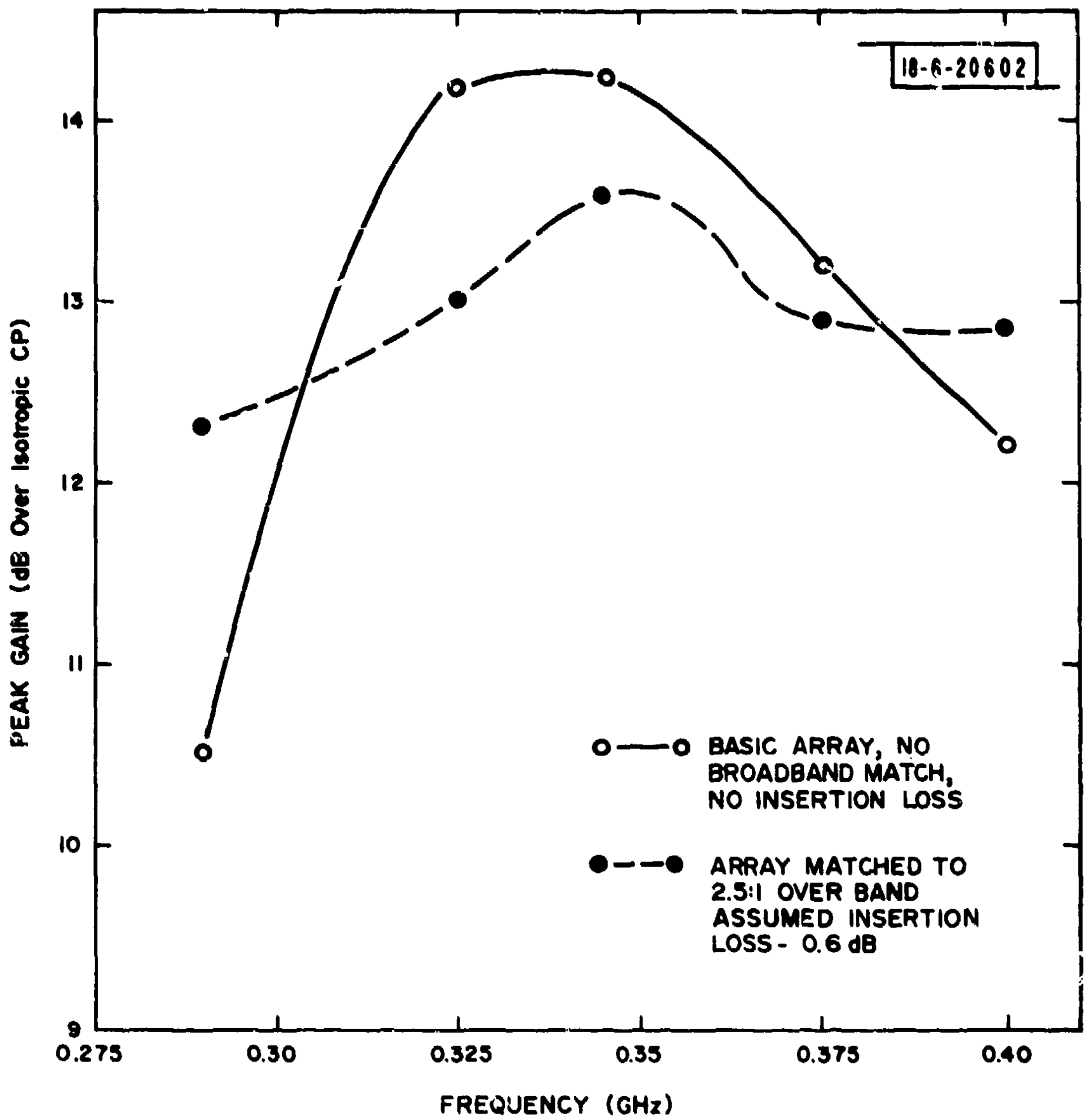


Fig. 2. Theoretical on-axis gain four element array.

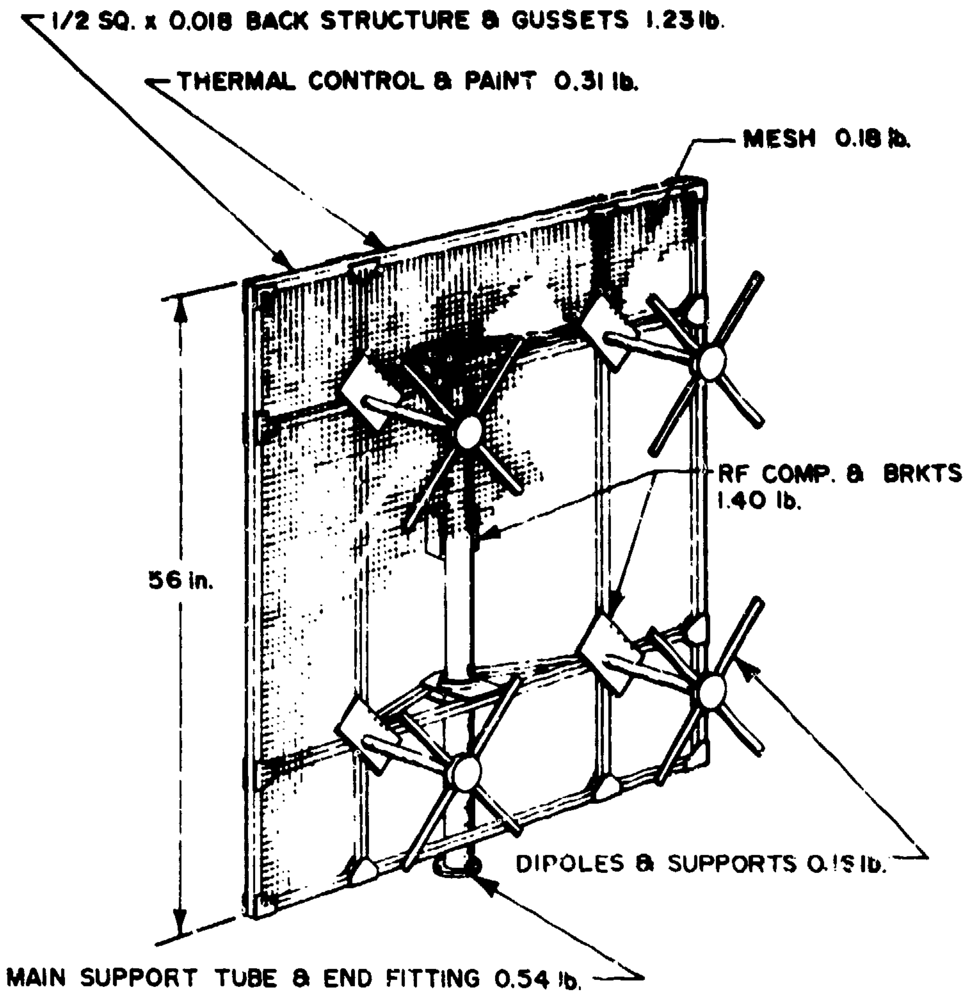
III. DEVELOPMENT

A. Mechanical

The development of the ground plane and back structure was almost entirely a mechanical design effort. However, the dipole development required close liaison between mechanical and electrical designers. The first element design considered, stripline dipoles fed by a strip-line feed network in the same plane, proved to be too heavy. Multi-layered substrates, required because of the cross-over of circuits in order to properly feed each dipole, and relatively heavy supports made this design unattractive. The final design (Fig. 3) incorporated strip crossed-dipoles fed by four microstrip lines which when combined with the last stage of a strip line distribution network, formed the required dipole balun. The network was permanently attached to the dipole and then, at assembly, fastened to the ground-plane structure. This method of assembly would allow for the individual testing of dipoles and their feed-networks anytime during the pre-flight test program and easy replacement if required.

To achieve a low-weight structure, graphite-epoxy materials were used to construct the ground plane. These composites have stiffness-to-weight ratios several times higher than any conventional structural metals, thus providing a dramatic reduction in weight while maintaining mechanical integrity. Further information on the ground plane and back structure details can be found in a companion report[1].

The actual reflecting surface of the ground plane consists of an open wire mesh. Each wire is made up of seven strands of stainless steel wire fused together with a single strand of silver. The total diameter of the bundle of strands is only 0.005 and the mesh opening is 3/8" square. This mesh, which has been previously space qualified on both FLEETSAT and LES-8/9 satellites, weighs only 0.007 pound per square foot and is welded at each wire junction. There is negligible difference in the reflecting capability of this mesh and a solid metal sheet when operating in the frequency band of interest.



TOTAL STRUCTURE WEIGHT	2.42 lb.
RF COMP. & SUPT. BRACKETS	1.40 lb.
TOT. WT. PER REC. ANT. ELEM	3.82 lb.

-6-20603

Fig. 3. Graphite/epoxy UHF receive antenna element.

The dipole support mast is made up of a 0.012 inch wall aluminum tube within a G-10 fiberglass dielectric tube which serves as the micro-strip substrate. Four copper-foil strips are equally spaced around the exterior circumference of the dielectric support mast to feed the dipole elements. The details of this feed system are shown in Fig. 4. The strips and, hence, each element of the crossed dipole, are fed in phase rotation (0°, 90°, 180°, 270°) to achieve the desired circular polarization. The radiating arms of the dipole are 0.005 inch thick by 0.500 inch wide beryllium copper strips which have been shaped during heat treatment and have stiffness properties similar to a steel tape rule (see Fig. 4).

B. Electrical

Because the system was to be operated over a relatively broad UHF band, initial RF development efforts were to broaden the characteristically narrow impedance band of a simple dipole as much as possible by varying the basic dipole dimensions. Further experimental external matching required exciting the entire dipole with the appropriate 180° phase difference between dipole elements while measuring the input impedance of each micro-strip line. Using the measured impedance data, a computer assisted design was carried out to find an appropriate matching network. A VSWR less than 2.5 was then obtained by adding a short-circuited stub and an impedance transformer section in the micro-strip line on the dipole support mast. The stub was located 5" below the dipole end of the support mast.

In addition to matching each dipole element, a strip-line distribution network for feeding the four lines to each dipole was designed and fabricated. The circuit schematic is shown in Fig. 5 and includes a coaxial 4-way power divider which connects to the four strip-line circuits. The insertion loss of the distribution network alone was found to be 0.6 dB, slightly higher than expected. The measured output phase at the network was within $\pm$ 15° of design values and the amplitude was within $\pm$ 0.3 dB of equality over the frequency band. A flight model array, including strip-line feed networks attached to dipoles, was then run through environmental tests with excellent results (see Ref. 1 for details).

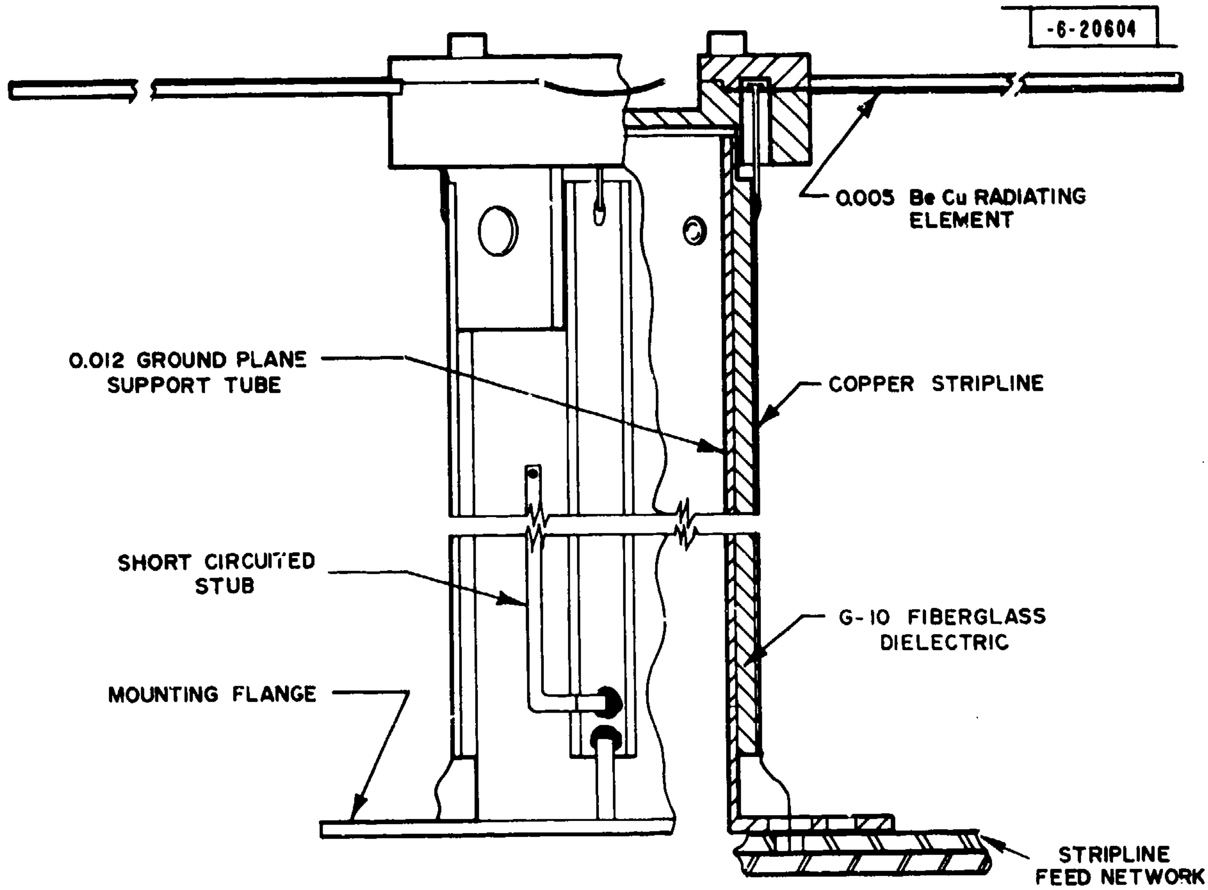


Fig. 4. Light-weight dipole element.

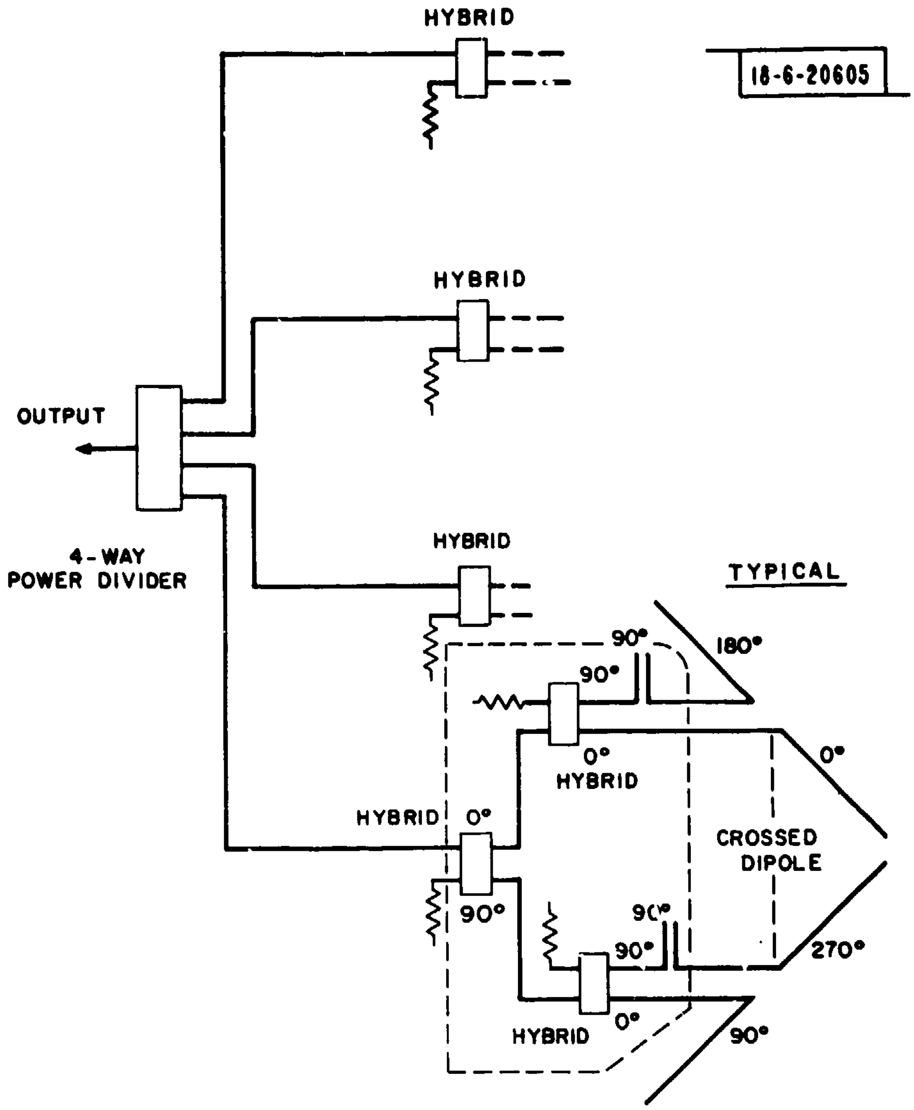


Fig. 5. Schematic of four element crossed dipole array.

Measured polarization performance indicates an axial ratio of less than 3 dB over the entire band. Measured gain compared with the theoretical calculations is indicated in Fig. 6. Differences between the two may be attributed to: the differences in total network losses (1.0 dB measured vs 0.6 dB estimated), the use of a finite ground plane, and variation of VSWR over the band. It was found during these measurements that by adding half inch wide, ten inch long parasitic loading strips, 1/4" above the dipole elements the maximum input VSWR was reduced from 2.5 to 2.3 and an on-axis gain improvement of 0.3 dB could be realized. The results in Fig. 6 include this modification. This addition is extremely light weight and improves the mechanical stability of the dipole element. The initial computed and measured impedance plots of a single dipole are shown in Fig. 7(a) and the final matched values with the parasitic strips are given in Fig. 7(b).

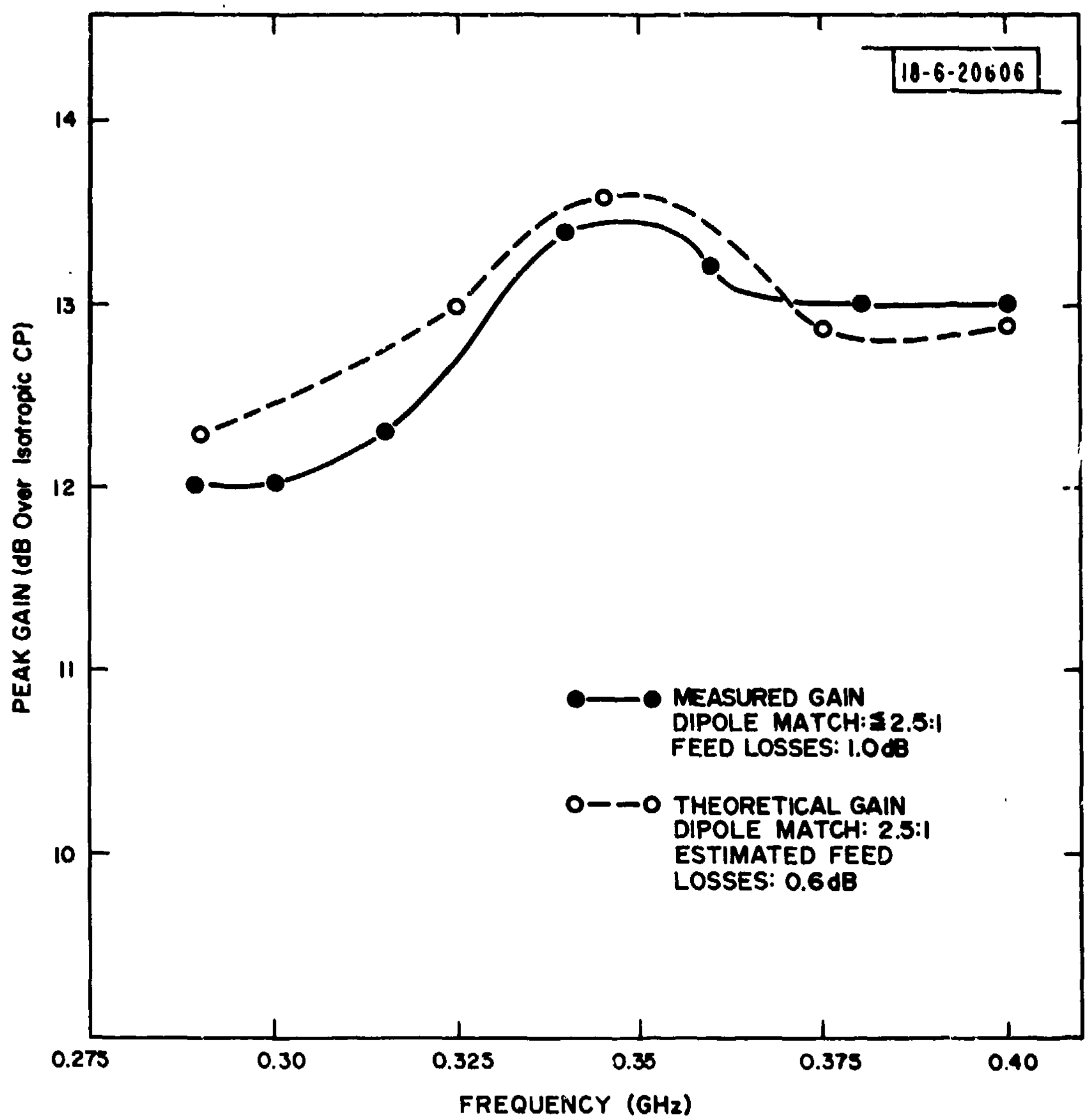


Fig. 6. Peak gain four element array.

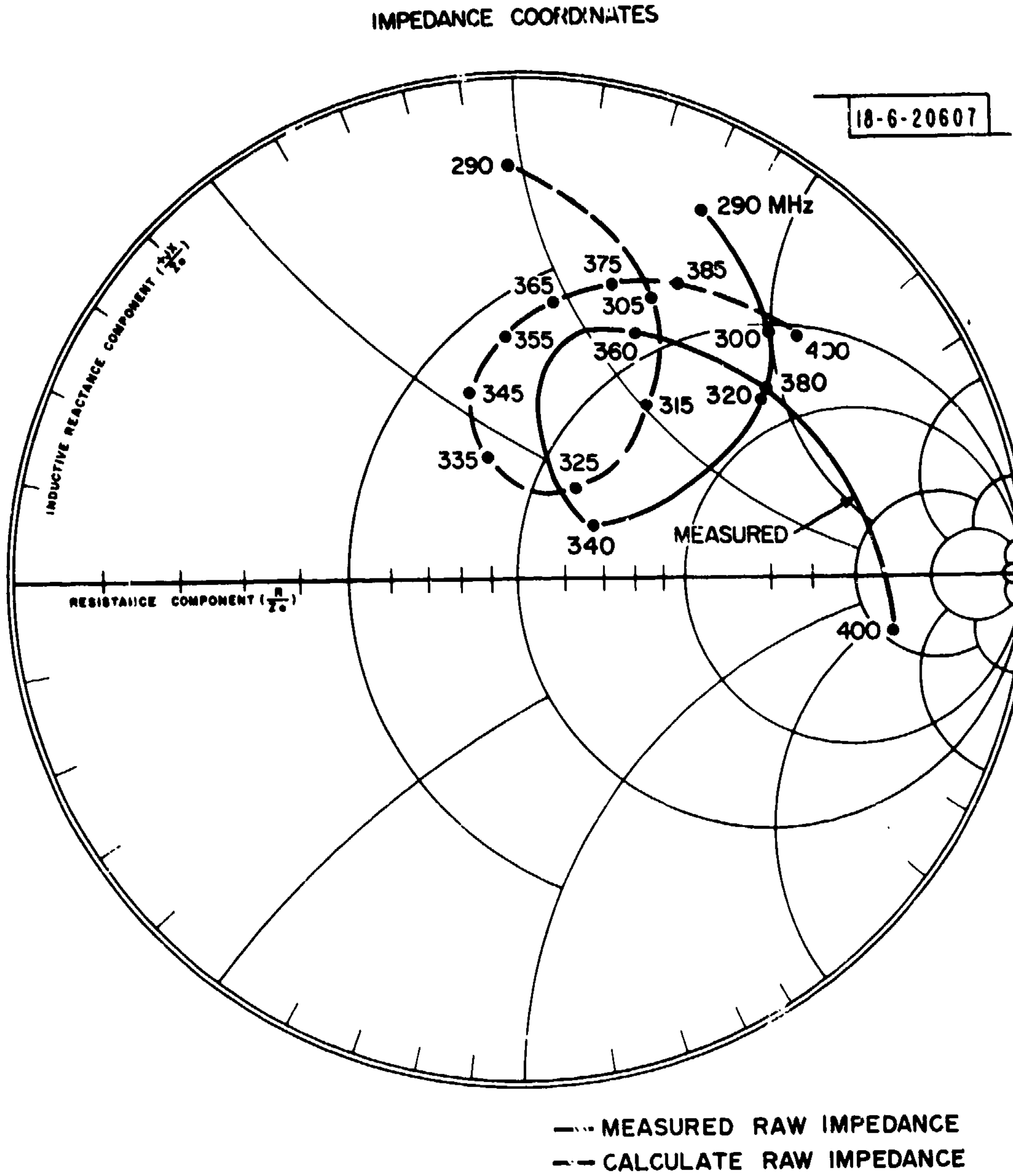


Fig. 7(a). Raw impedance of single light-weight dipole.

IMPEDANCE COORDINATES

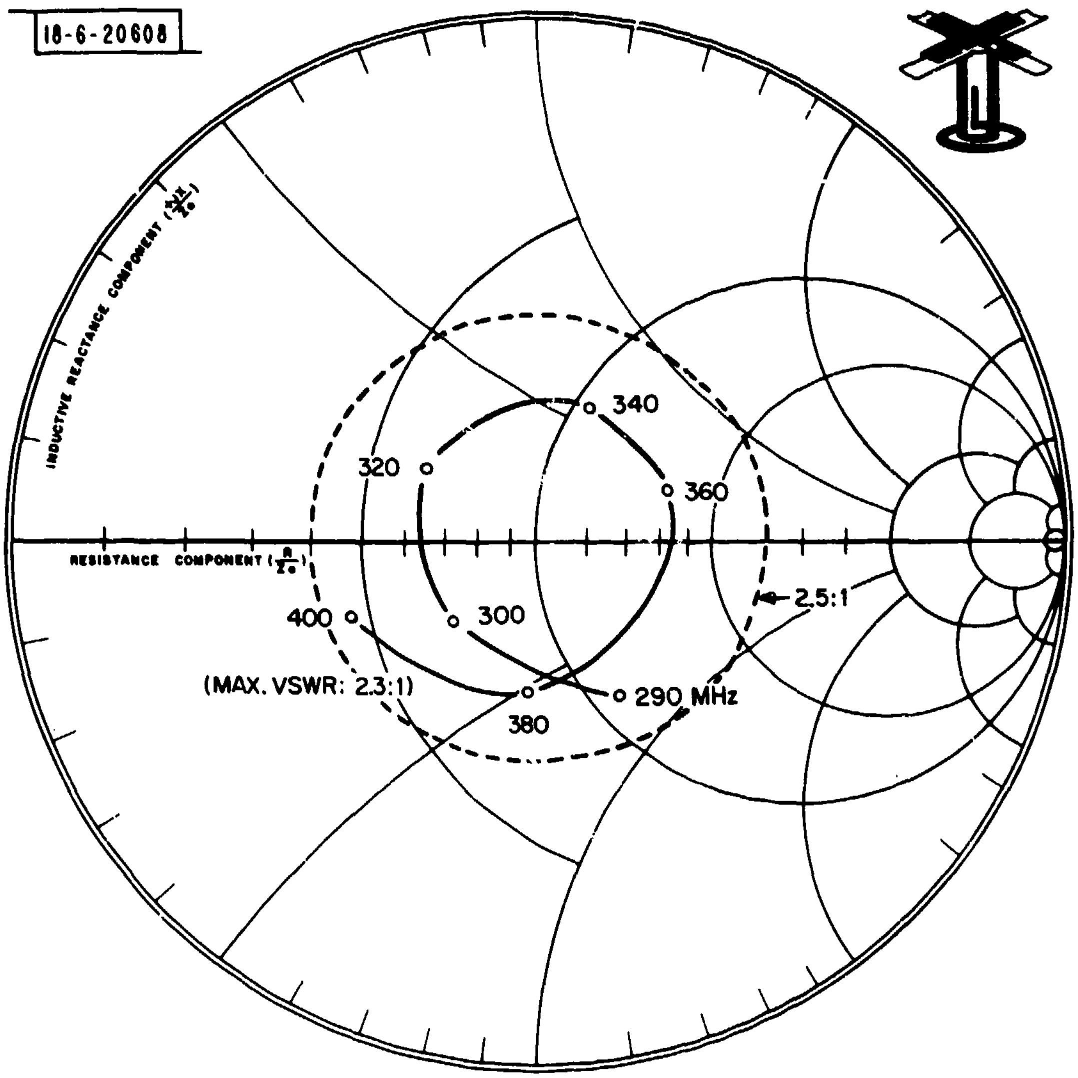


Fig. 7(b). Final impedance of a single light-weight dipole.

IV. SYSTEM CONSIDERATIONS

A. Array Coupling Factors

Several overall system configurations were considered in addition to that shown in Fig. 1. In each case receive arrays near or on the satellite centerline would be in close proximity to a UHF transmit array. Concern that transmit power would not be adequately decoupled from the receiver elements prompted an investigation of the coupling factor: 1) between dipoles mounted on a common ground plane as a function of spacing between them and 2) between two arrays of dipoles on their individual ground planes as a function of the spacing between array (and, therefore, ground plane) centerlines.

Fig. 8 indicates this coupling factor as a function of spacing in wavelengths. For the arrays, the value of coupling is from array input to the adjacent array output and the spacing is the array centerline to centerline distance. The oscillations noted on the array curves are caused by the addition and cancellation of scattered signals off the ground plane edges of the two arrays.

B. Stowing of a Large Thinly Spaced Array

Because the antenna system was to be launched into space utilizing the space shuttle launch vehicle certain development efforts had to be directed toward folding the out-rigger elements into a package conforming to the booster usable area. A folding arm graphite-epoxy boom, 2" in diameter was developed which was strong and light-weight but also insured extreme reliability in the unfurling operation. The boom assembly, including deployment mechanism, weighed less than 5.0 pounds and was eighteen feet long. This design and its mechanical characteristics are described in detail in Reference 1 and is shown in Fig. 9. It was planned to connect the array and satellite circuitry with air-filled coaxial lines or micro-strip; in either case making weight and insertion loss the prime factors. Passage through the boom joints was to be accomplished with contacting rotary joints because flexible cables were found to lose their flexing characteristic at normal space temperatures. Contacting rotary joints

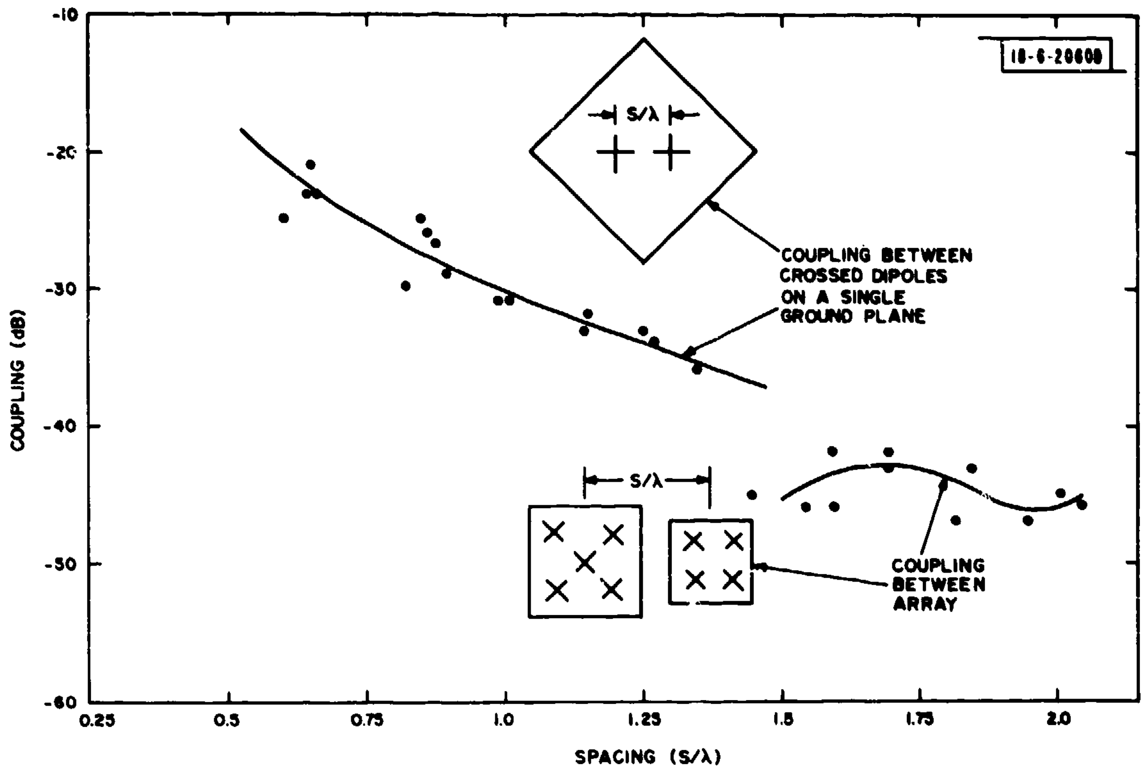


Fig. 8. Coupling between crossed dipole elements and arrays.

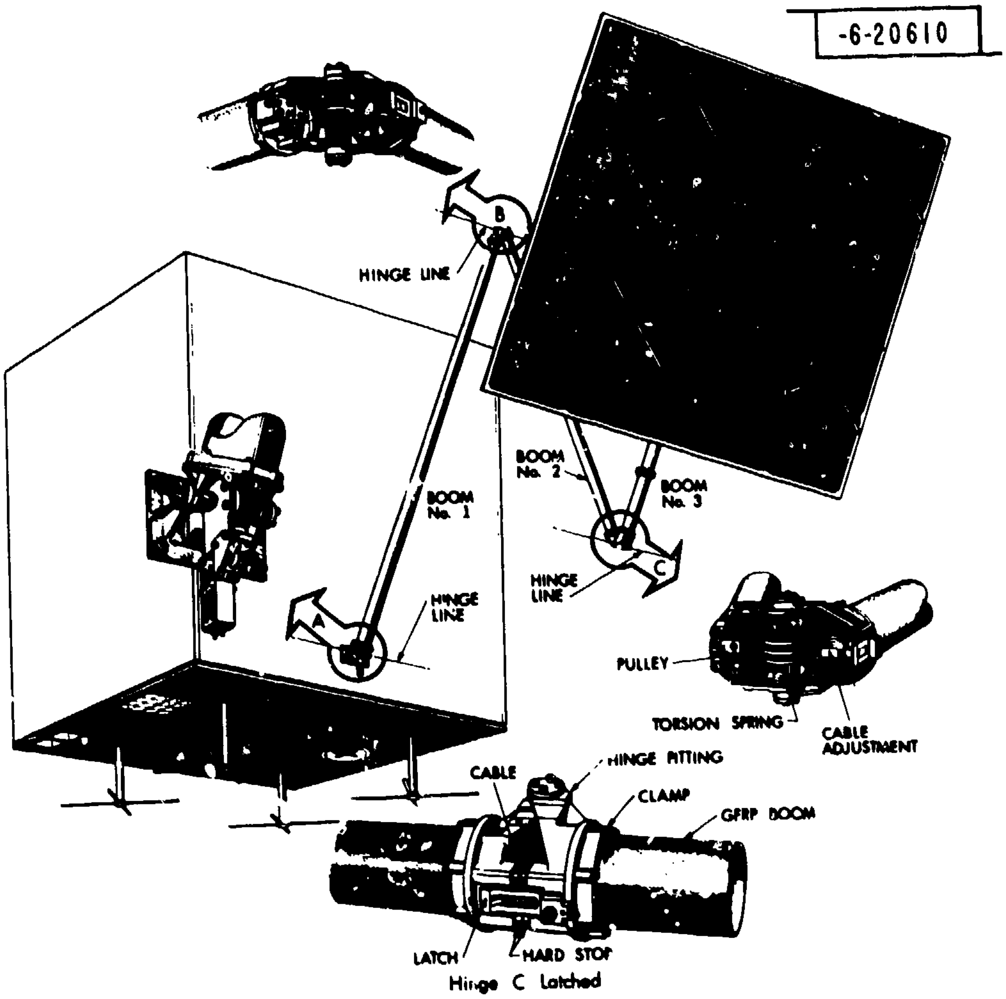


Fig. 9. Boom deployment system.

were considered satisfactory because the rotation would only take place once, at deployment on orbit, and so contact wear with extended use would not be a problem.

C. Intermodulation Effects

Preliminary testing indicated it was possible to design a radiator that had satisfactory gain and VSWR and was extremely light weight. Therefore, an investigation was also initiated to determine the intermodulation (IM)* characteristics of the antenna. A test program was scheduled to determine the IM generated by: a) the graphite/epoxy backstructure, b) the silver and stainless steel stranded mesh ground plane, c) the fabrication and assembly techniques of the feed network, and d) several types of coaxial connectors which could be used at the network inputs. Connector and basic material test results and test set-ups are described elsewhere[2]. The basic measurement consists of combining the outputs of two transmitters through a suitable filter network, and measuring the spurious signal power generated by the device under test. Three distinct measurements were carried out on the light-weight antenna. They were low power transmitting, high power receiving, and light-weight ground plane high-power reflecting tests.

The tests were conducted in an anechoic chamber with equipment whose combined IM generation (-147 dBm) was equivalent to the maximum tolerable IM level of a typical UHF receiver. The first test, a low power transmitting test, utilized a single light weight antenna connected to a two-channel transmitter of +17 dBm per channel. This power level was chosen to simulate a postulated -30 dB coupling from a transmit antenna at +47 dBm to the light-weight antenna used as a receiving antenna. The frequencies of the two channels were 245 and 268 GHz. The overall 3rd order IM level at a frequency of 291 MHz generated by a single dipole, complete ground plane, and hybrid network

*When two or more transmit frequencies are used simultaneously in the same circuit it is possible to generate in the receive frequency band spurious intermodulation products providing there exists some nonlinear mechanism in the transmit/receive networks. Degradation of receiver sensitivity results if these spurious signals are stronger than the level of the receiver noise.

was measured to be -144 dBm, which was marginally acceptable. This IM signal was measured at the receiving port of a transmit-receive diplexer connected to the antenna.

The high power receiving test was next done. In this setup a dipole antenna, specifically designed to be a low generator of IM, was connected to the dual-frequency source mentioned above but at a power level of +44 dBm per channel. The full 4-element light-weight array was then assembled and placed adjacent to the ground plane on which the transmit dipole was mounted, both antennas facing in the same direction and 26 inches apart. The 3rd order IM signal at the light-weight receive antenna varied between -102 and -107 dBm. These relatively high levels of IM are thought to be generated in the light-weight antenna itself, by coupling of the two transmit frequencies to the antenna. In an attempt to verify that the IM was not generated externally, a helix antenna with a radiation pattern similar, but not identical, to that of the dipole array was designed for low IM generation and was mounted in place of the array. Its apparent 3rd order IM generation was at the -134 dBm level.

The light-weight ground plane, high-power reflecting test was next done to determine the contribution to the IM of the ground plane alone. The low-IM short helix antenna was used as a receiving antenna and either a solid aluminum ground plane or the light-weight ground plane was placed between the transmit and receive antenna. Depending on the spacing of the devices the reflected IM at the transmit dipole input port increased by 8 to 20 dB and the receive IM level at the helix output port increased from 8 to 38 dB when the aluminum ground plane was replaced with the light-weight ground plane assembly, indicating that the graphite-fiber and mesh construction was a potential intermod generator.

Changing program emphasis at the Laboratory precluded a complete evaluation of the potential IM problem, or evaluation of contemplated changes that could improve the IM levels of the array. However, it would be proper to conclude that the light-weight antenna described herein could be used as a receiving antenna either in a system where IM was not a problem (i.e., single transmit

frequency), or where physical separation of transmit and receive antennas is enough to take advantage of the natural isolation of separated antennas.

V. CONCLUSIONS

An extremely light weight circularly-polarized UHF crossed-dipole array has been designed and fabricated. Consisting of four dipoles, their feed network, 56" x 56" ground plane and its back structure, the entire structure weighs only 4 pounds. The array provides a measured nominal +13 dB gain and is circularly polarized wth an axial ratio under 3 dB over the entire 290-400 MHz frequency range. The unit passed all environmental tests undertaken, and, therefore, is an excellent candidate for satellite receiving antenna applications.

ACKNOWLEDGMENT

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